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Discussion of the paper

A Working Hypothesis for
Further Studies of Frost
Resistance of Concrete

BY
T. C. POWERS

Discussion by:

Ruth D. Terzaghi, Douglas McHenry and H. W. Brewer,
A. R. Collins, and Author

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Discussion of a paper by T. C. Powers:

**A Working Hypothesis for Further Studies of Frost
Resistance of Concrete***

By RUTH D. TERZAGHI, DOUGLAS McHENRY and H. W. BREWER,
A. R. COLLINS and AUTHOR

By RUTH D. TERZAGHI*

SCOPE OF DISCUSSION

In his stimulating article on the frost resistance of concrete, Mr. Powers has described a possible mechanism of the disruption of concrete by freezing. In this discussion an attempt will be made to find out whether this mechanism might lead to the disruption of concrete in the field. According to Mr. Powers' hypothesis, disruption may be due to the development of a high hydrostatic pressure in the pore water of concrete adjacent to the zone of freezing. As Mr. Powers has pointed out, this process can be effective only if the concrete is saturated to a certain minimum depth which he terms the critical depth of saturation. Hence we may test the applicability of this hypothesis to field conditions by estimating this depth for concrete of given properties, exposed to natural winter weather, and comparing our estimate with the depth to which such concrete is likely to be completely saturated under normal conditions. Such an estimate is presented in the section on "Critical Depth of Saturation." The results of the estimate suggest that disruption of lean concrete under natural climatic conditions is due to some process other than that postulated by Mr. Powers.

Another topic with which Mr. Powers' article deals is the classification of the pores which contain freezable water. To the two categories of such pores mentioned by Mr. Powers, the present writer would add a third, consisting of the capillary spaces between aggregate and paste. Evidence for the existence of such spaces is presented under the heading "Locus of Freezable Water."

*ACI JOURNAL, Feb. 1945; *Proceedings* V 41, p. 245.

†Geologist, Winchester, Mass. (now cooperating with her husband, Karl Terzaghi on a textbook on engineering geology).

A part of Mr. Powers' article is devoted to a previously stated hypothesis that ice lenses, analogous to those which develop in some soils and sediments, may form in concrete. His conclusions regarding this hypothesis are based in part on the opinion that such ice lenses do not form in relatively impermeable soils. This opinion is not supported by observations of geologists, which are discussed under the heading "Conditions for the Formation of Ice Lenses in Soils and Sediments."

CRITICAL DEPTH OF SATURATION

The purpose of this section is to evaluate the extent to which Mr. Powers' hypothesis may be applicable to the disruption of concrete by frost under natural climatic conditions. The basis for the evaluation is provided by an estimate of the critical depth of saturation corresponding to the most unfavorable winter conditions likely to be encountered.

For concrete with given properties, exposed to natural winter climate, the critical depth of saturation depends on two quantities. These are the rate of decrease of the air temperature from about 32 F to several degrees below that temperature, and the pore water pressure necessary to produce rupture. The first of these is determined by climatic conditions and is probably never in excess of 5 F per hour. The second quantity, the pore water pressure at rupture, is a function of the tensile strength of the concrete and of the shape of the voids.

Published experimental data* indicate that the shape of the voids of concrete is such that the pore water pressure is transmitted to at least 97 per cent of the cross section. Hence we must conclude that the pore water pressure at rupture is approximately equal to the tensile strength of the concrete. This conclusion is incompatible with Mr. Powers' estimate (page 253) that the pore water pressure must become equal to about five times the tensile strength of the concrete in order to damage it. However, the critical depth of saturation will be determined on the basis of both assumptions.

In the following paragraphs, equations will be derived which express the relation between the critical depth of saturation, the rate of temperature decrease of the surroundings, and the pore water pressure at rupture. Conditions at the time of rupture are illustrated by Fig. A.

The symbols which will be used are as follows:

C = constant of integration.

K = coefficient of permeability of the concrete, in cm per sec.

L = latent heat of water per gram = 80 calories.

n = volume of freezable water per unit of volume of saturated concrete.

*Terzaghi, Karl, "Die wirksame Flächenporosität des Betons," *Zeitschrift des Oesterreichischen Ingenieur- und Architekten-Vereines*, Heft 1/2, 1934. See also a forthcoming article by the same author "Stress Conditions for the Failure of Saturated Concrete and Rock," *Journal American Society for Testing Materials*.

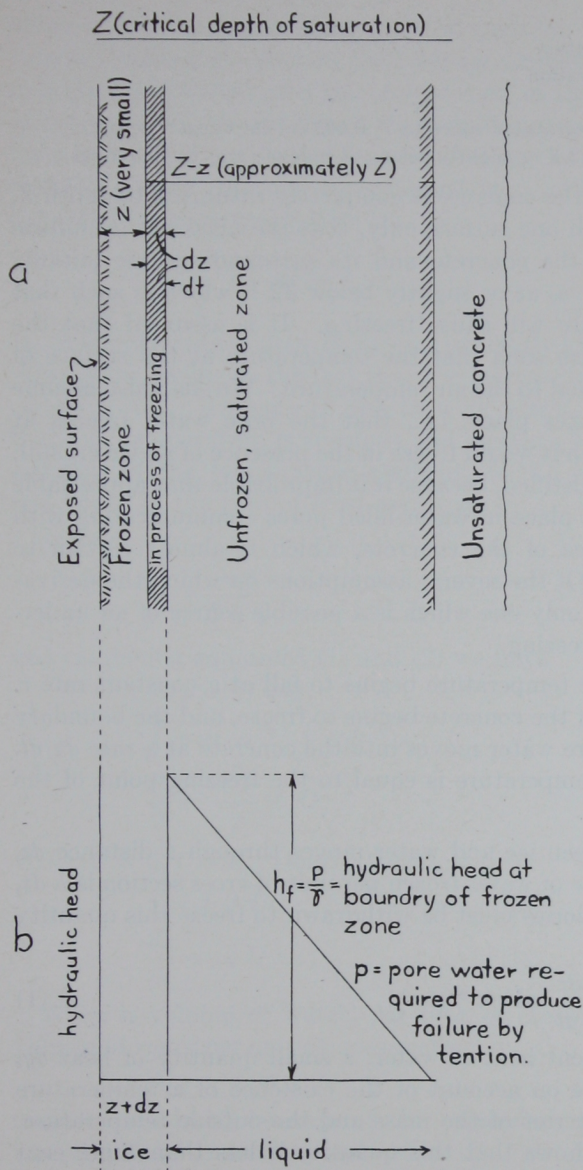


Fig. A—Diagram illustrating conditions during freezing of pore water in saturated zone. a) Cross section through concrete saturated to critical depth Z ; b) Hydraulic pressure conditions in unfrozen saturated zone at moment of rupture.

p = hydrostatic pressure in pore water at failure, in gm per sq. cm.

q_c = calories withdrawn from concrete, per unit of area of cross section.

q_w = volume of water displaced, per unit of area of cross section, owing to expansion accompanying freezing.

r = maximum rate of temperature change in degrees centigrade per second under normal climatic conditions, assumed equal to -0.0008 deg. C per sec., corresponding to -3 C (-5 F) per hour.

- t = time in seconds
 z = depth of frost penetration
 Z = critical depth of saturation
 γ = unit weight of water
 λ = heat conductivity of saturated concrete = $0.003 \text{ cal cm}^{-1} \text{ degC}^{-1} \text{ sec}^{-1}$ *.
 θ_0 = initial temperature, 32 F or slightly below, of concrete and surroundings.

We shall assume that the concrete is completely saturated to depth Z , that it loses heat through one surface only, that the mass has a uniform cross section, and that the concrete and its surroundings are initially at the same temperature θ_0 at or slightly below 32 F which is such that a decrease of temperature will cause freezing. It is assumed that the conditions of exposure are such that the temperature at the surface of the concrete is always equal to the air temperature. We shall also assume that no supercooling takes place, i.e., that the pore water freezes at that temperature at which it would freeze in the presence of an ice crystal. This assumption seems justified, because it is improbable that appreciable supercooling would take place in water-filled pores communicating with free water at the surface of the concrete, which is almost certain to freeze at or near 32 F. Of the several assumptions on which the derivation is based, this is the only one which is a possible source of an underestimate of the rate of freezing.

At time $t = 0$, the air temperature begins to fall at a constant rate r . The water in the pores of the concrete begins to freeze, and the boundary between pore ice and pore water moves into the concrete at a rate dz/dt . At this boundary, the temperature is equal to the freezing point of the pore water θ_0 .

If the boundary between ice and water moves through a distance dz , the corresponding volume of water frozen per unit of cross section is $n dz$, and the rate at which calories must be withdrawn to freeze this quantity of water is

$$\frac{dq_c}{dt} = L n \gamma \frac{dz}{dt} \text{ cal cm}^{-2} \text{ sec}^{-1} \dots \dots \dots (1)$$

In addition to the latent heat of water, a small quantity of heat dq_c flows out of the concrete on account of the existence of a temperature gradient between the interior of the mass and the outside temperature. A simple computation shows that this quantity is less than 1 per cent of dq_c as long as z does not exceed a few centimeters. Hence it does not require consideration.

The rate at which heat is withdrawn from the zone of freezing, per unit of area of the surface of cooling, is equal to the heat conductivity of the concrete multiplied by the temperature gradient in the concrete

*Knoblauch, Raisch, and Reiher, *Gesundheits Ingenieur*, v. 43, p. 607, 1920; cited in *International Critical Tables* (1927) v. 2, p. 314.

between the zone of freezing and the surface. The temperature in the zone of freezing is equal to the freezing temperature of the pore water, θ_0 , which is identical with the temperature of the entire mass of concrete at time $t = 0$. At any time t , the temperature of the surface of the concrete is $\theta_0 + rt$, and the distance between the surface and the zone of freezing (depth of frost penetration) is z . Hence the rate at which calories are withdrawn at time t is

$$\frac{dq_c}{dt} = \frac{\lambda r t}{z} \text{ cal cm}^{-2} \text{ sec}^{-1} \dots\dots\dots (2)$$

In reality the temperature at depth z is slightly lower than θ_0 when rupture takes place, owing to the fact that the increase in pressure from zero to p causes a slight decrease in the freezing point. Hence our assumption that this temperature is constant and equal to θ_0 results in a slight overestimate of the temperature gradient, of the rate of heat withdrawal, and hence of the rate of frost penetration.

Setting

$$U = \frac{\lambda r}{L n \gamma}$$

and combining equations (1) and (2) we have

$$\begin{aligned} z \, dz &= U \, t \, dt \\ \int z \, dz &= U \int t \, dt \\ \frac{z^2}{2} &= \frac{U t^2}{2} + C \end{aligned}$$

When $z = 0$, $t = 0$. Hence $C = 0$, and

$$z = t \sqrt{U} \dots\dots\dots (3)$$

$$\frac{dz}{dt} = \sqrt{U} \dots\dots\dots (4)$$

When a volume of water, per unit of cross-section, $n \, dz$, freezes, a volume of water per unit of cross-section

$$dq_w = 0.09 \, n \, dz$$

must be displaced because of the expansion attending freezing. The rate at which it must be displaced is

$$\frac{dq_w}{dt} = 0.09 \, n \, \frac{dz}{dt} \text{ cm sec}^{-1} \dots\dots\dots (5)$$

The quantity dq_w/dt is equal to the coefficient of permeability of the concrete multiplied by the hydraulic gradient. Both theory and experience indicate that rupture (spalling) takes place near the exposed surface. Hence the hydraulic gradient at rupture is approximately $p/\gamma Z$, and the

initial rate at which water is displaced from the zone of freezing to the inner edge of the saturated zone is given by the following equation:

$$\frac{dq_w}{dt} = \frac{Kp}{Z\gamma} \text{ cm sec}^{-1} \dots\dots\dots (6)$$

Combining equations 4, 5 and 6, we have

$$Z = \frac{Kp}{\gamma \cdot 0.09 n \sqrt{U}} \text{ cm} \dots\dots\dots (7)$$

U may be evaluated with sufficient accuracy for present purposes from the data given in the list of symbols. Using these values we find

$$U = \frac{3 \times 10^{-8}}{n} \text{ cm}^2 \text{ sec}^{-2}$$

$$\sqrt{U} = \frac{dz}{dt} = 1.73 \times 10^{-4} \sqrt{1/n} \text{ cm sec}^{-1} \dots\dots\dots (8)$$

The critical depths of saturation for severe winter conditions, calculated by means of equation (7) for the rich and for the lean concrete described by Mr. Powers on page 255, are 0.2 in. and 7 in. respectively, if rupture takes place at a pore water pressure equal to the tensile strength of the concrete. If this pressure must reach a value equal to five times the tensile strength in order to cause appreciable damage, as assumed by Mr. Powers, the corresponding values of the depth of saturation are 1 in. and 35 in. respectively. A depth of saturation of 7 in., even in lean concrete, is probably not common, and it does not seem likely that frost damage to such concrete is limited to those situations where it is saturated to this depth. Hence we must conclude that frost damage to lean concrete exposed to natural climatic conditions is generally due to some process other than that postulated by Mr. Powers.

LOCUS OF FREEZABLE WATER

Mr. Powers has listed two classes of space of capillary dimensions in concrete, likely to contain freezable water. To these the present writer would add a third, consisting of the space between aggregate, particularly the coarse aggregate, and the paste. Evidence of the existence and relative importance of these spaces is found in the condition of some specimens of concrete recently examined by the writer, as well as in the appearance of laboratory specimens of concrete described by Merkle. This evidence is presented in the following paragraphs.

The specimens examined by the writer are drill cores taken from a large mass of concrete two years after casting. The water-cement ratio of the concrete (by weight) was 0.53. The specimens showed no evidence of internal bleeding, of segregation, or of other original defects which

might have resulted in the presence of abnormal cavities in the concrete. One face of the structure is in contact with sea water and one face is exposed to the atmosphere. Sea water enters the concrete under a hydraulic gradient which varies from place to place between about one and about five. Its access to the interior of the structure has been facilitated by the presence of cracks which developed progressively and had become conspicuous two years after casting. In specimens taken from this structure, within a zone whose upper surface slopes away from the sea-face, each of the medium-sized and large pieces of aggregate, with a diameter of about one-quarter inch to three inches, bears on its surface a more or less continuous film of fresh ettringite ($3\text{CaO} \cdot 3\text{CaSO}_4 \cdot \text{Al}_2\text{O}_3 \cdot 31\text{H}_2\text{O}$). In most of the specimens there is little or no ettringite on aggregate smaller than about one-quarter inch. The films are commonly a few hundredths of a millimeter (about one-thousandth of an inch) thick; exceptionally they are as thick as one-quarter of a millimeter. The thickness of the film on a given piece of aggregate is uniform. In a few specimens, the surface of coarse aggregate bears a deposit of ettringite which has been in part replaced by calcium carbonate and other substances. In these specimens, the medium-sized and finest aggregate is commonly covered with a deposit of unaltered ettringite.

The present writer's interpretation of these features is based on the following considerations. Although the constituents of the ettringite may have been derived in their entirety from the paste, the actual distribution of readily visible ettringite crystals can be explained only on the assumption that percolating sea water was necessary for their formation. Likewise, the local replacement of ettringite on coarse aggregate by calcium carbonate can be attributed only to the percolation of water (doubtless sea water) containing calcium bicarbonate or carbonic acid in solution, following the deposition of ettringite. We must, therefore, conclude that water has seeped through the concrete along the contact between aggregate and paste. Since the results of this percolation are most conspicuous at the contact between coarse aggregate and paste, the seepage velocity was doubtless most rapid along these contacts.

Evidence of a similar nature was described by G. Merkle*, who found conspicuous deposits of calcium carbonate at the contact between paste and coarse aggregate in laboratory specimens of concrete through which water with a high calcium bicarbonate content had percolated.

Whether a capillary space between aggregate and paste is universally present in concrete, or only under certain conditions, is of course an open question. Wherever such spaces are present, they would doubtless be among the first to be drained under drying conditions and the first to be

*Durchlässigkeit von Beton, Berlin 1927.

refilled when the concrete comes in contact with water. Under certain circumstances, water contained in them might play an important part in the disruption of concrete by freezing.

CONDITIONS FOR THE FORMATION OF ICE LENSES IN SOILS AND UNCONSOLIDATED SEDIMENTS

On the basis of evidence from several sources, Mr. Powers concludes that the formation of ice lenses in concrete, analogous to those formed in soils and sediments, is unlikely. One line of evidence is stated as follows:

"Inferred evidence against applying the Taber hypothesis of ice lense formation comprises those factors and observations indicating that concrete must freeze as a 'closed system,' whereas segregation of ice i.e., formation of ice lenses, can occur only in 'open systems'." (Closed systems are those whose total water content does not change, owing either to the low permeability of the material comprising it or to the inaccessibility of water.) The implication that ice-lense formation is limited to relatively permeable materials is not in agreement with observations by geologists regarding the conditions of ice lense formation in soils and sediments. It would therefore represent a service to all concerned if Mr. Powers would present in detail the observations on which his statement is based.

Observations made by Taber* in the laboratory may be summarized as follows:

Very slight segregation took place in ground quartz with an average particle size between 6 and 10 microns. Precipitated barium sulphate, very uniform in size, having an average particle diameter of about 2 microns and a maximum diameter of about 3 microns, gave well-defined segregation under favorable conditions of cooling, but no segregation under unfavorable conditions. In materials having a particle size of about 1 micron or less, segregation took place readily. Ice layers formed without difficulty in all of the clays investigated by Taber.

Similar observations regarding the influence of grain size were made by Beskow† both in the field and in the laboratory.

In these observations, there is nothing to indicate that low permeability is an obstacle to ice-lense formation. On the contrary, ice lense formation takes place most readily in the relatively impermeable soils. Hence the question as to whether or not ice lenses can or do form in concrete must be answered on the basis of other evidence.

*Taber, Stephen, "Frost Heaving," *The Journal of Geology*, vol. 37, 1929, pp. 427-517.

†Beskow, Gunnar, *Soil Freezing and Frost Heaving*, Swedish Geol. Surv., Series C, No. 375, 26 Yearbook No. 3, Stockholm 1935.

By DOUGLAS McHENRY and H. W. BREWER*

Mr. Powers has attached a very formidable problem with commendable courage and with a degree of scientific detachment which permits no delusions regarding the complexities of the problem or the possibility of resolving its many dilemmas by the application of a single hypothesis. The writers find no fault with the hydraulic pressure hypothesis—nor indeed with any major phase of the paper—provided it is viewed as intended by the author as “a working hypothesis which, together with other hypotheses, may eventually lead to the desired solution.” The comments in this discussion, based largely on experimental work in the laboratory of the Bureau of Reclamation, are not intended to simplify the problem, but rather to emphasize its complexities and the need for further study and still other hypotheses. For example, in accounting for the variable effect of increased hydration on durability, the author lists three pertinent effects:

1. It reduces permeability.
2. It reduces the amount of freezable water.
3. It possibly increases the initial degree of saturation.

According to the hypothesis a reduction in permeability and an increase in degree of saturation are detrimental to durability, while a reduction in the amount of freezable water is beneficial. To the above three pertinent effects at least three others might well be added:

4. It reduces the amount of cement available for autogenous healing.
5. It reduces the ability to creep.
6. It increases the tensile strength.

Thus, at least six factors enter into this phase of the problem, and of these 2 and 6 are favorable while 1, 3, 4, and 5 are unfavorable to durability. Even for a particular concrete it appears that the relationship between durability and degree of hydration is not a simple one. The Bureau of Reclamation has conducted tests in which the mixing and initial curing temperatures were 40, 60, 80 and 100 F. These temperatures were maintained for 24 hours, after which the specimens were fog cured at 70 F for 180 days. The number of cycles of freezing and thawing required to produce an expansion of 0.6 percent was 310, 450, 300, 245, respectively. Apparently for this concrete there is a certain optimum curing temperature, and presumably an optimum degree of hydration, to produce maximum durability under the conditions of test employed.

The author did not discuss the healing effect of continued hydration during the freezing and thawing period, but the writers believe that this may often be a significant factor with respect to durability—especially under laboratory conditions in which the tests are started at an early age.

*Bureau of Reclamation, Denver, Colo.

Reagel* has reported tests which show that thawing at 40 F causes more rapid breakdown than thawing at 90 F, and his results have been confirmed by Hornibrook.† It is inferred from the author's discussion of

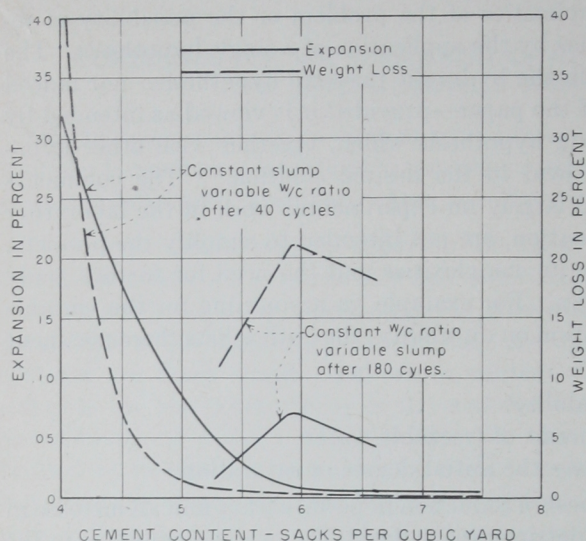


Fig. B—Durability of 3 x 6 in. concrete cylinders.

“Factors governing the amount of water absorbed during thawing” that from consideration of hydraulic pressure alone the reverse should be true because a more rapid melting of the surface ice permits greater absorption during the thawing period. Hornibrook has attributed the greater resistance with a higher thawing temperature to repair by autogenous healing, and it may be that this effect overshadows the effect of the greater absorption discussed by the author.

The results of the freezing and thawing tests on the concrete shown by Fig. 2 are contrary to all test results obtained in this laboratory. Fig. B of this discussion shows expansion and weight loss curves for two typical test series. In both instances the expansion and weight change curves are similar. The writers know of no test results by others which confirm the author's Fig. 2, and it seems that his results must be attributed to some unusual combination of circumstances.

The author mentions fissures under the aggregate particles as one type of cavity which may affect resistance to weathering, but it is not clear whether he attributes to them an increase or a reduction in durability. The writers believe that these fissures contribute to low durability, especially in concrete which bleeds freely. In permeability tests in which

*F. V. Reagel, “Freezing and Thawing Tests of Concrete.” Proc. Highway Research Board, v. 20, p 587 (1940).

†F. B. Hornibrook, Discussion of foregoing reference.

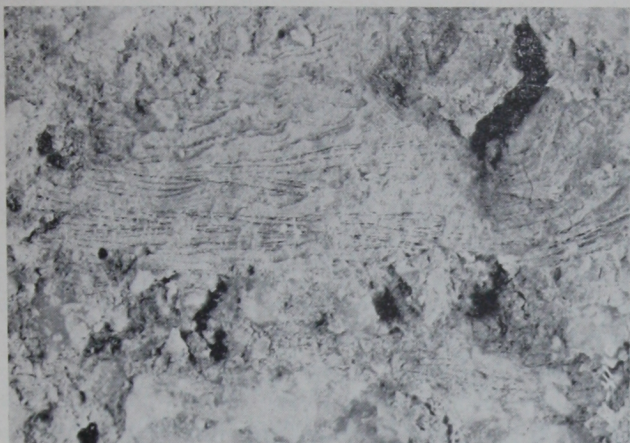


Fig. C—Ice segregation resulting from slow freezing starting when the concrete was 4 hours old — magnified $4\frac{1}{2} \times$

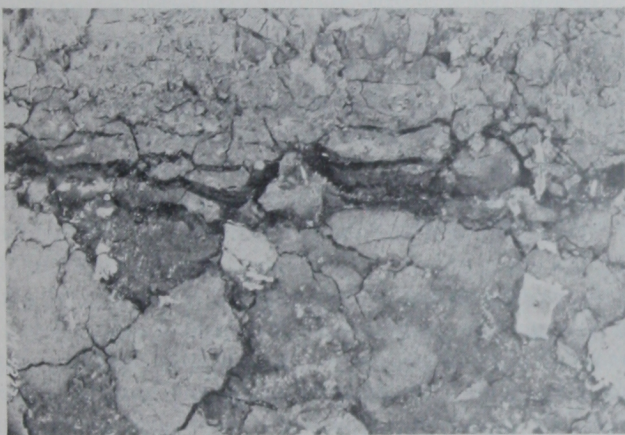


Fig. D—Ice lens formed in soil of permeability corresponding to that of moderately tight concrete—magnified $3 \times$

dye was used, the greatest concentration of dye was always found in the fissures between the aggregate particles and the paste. Observation of frozen concrete and of disintegrated concrete with the binocular microscope indicates that ice forms readily in such fissures, and that it exerts a disruptive effect by loosening the aggregate particle from its socket. This condition was especially pronounced in cylinders which were frozen slowly from the top downward with the bottom immersed in water. It is considered not unlikely that the concentration of ice in these regions of low tensile strength is closely related to the segregation which the author has discussed under the heading "The Taber-Collins Hypothesis." The writers have not observed any other type of segregation in mature concrete, although distinct lenses have been produced in concrete which was frozen slowly starting when the concrete was only four hours old (Fig. C).

The author remarked on the absence of permeability data on soils which showed ice segregation, but concluded that for concrete "the degree of permeability alone precludes the formation of lenses under the usual rates of cooling." The writers used Taber's technique in testing a cylinder of saturated clay having a permeability coefficient of 1370×10^{-8} feet per day, corresponding to concrete of moderate permeability, and found that a single freezing produced a lens about 1/16 in. thick extending over the entire cross-section of the cylinder (Fig. D). The rate of freezing was slower than the usual rate for freezing and thawing tests, but was not too slow to be representative of some field conditions. The test suggests that the tensile strength, rather than the impermeability, accounts for the usual absence of visible lenses in concrete.

Some test data which have been reported in the literature suggest that the author's figure of 2500 psi as the internal force required to produce disruption of concrete may be too high by a considerable amount (at least, for saturated specimens). Perhaps the best of such data are given by Leliavsky*, who determined the pore pressure required to fracture concrete tubes subjected to axial and circumferential pressures. He concluded that the pore pressure acted over about 92 percent of the cross-sectional area, and that "The fraction of the area of cross-section over which the internal pressure acts can therefore have nothing to do with ordinary porosity." Terzaghi† had previously been led to a similar conclusion by measuring the effect of pore pressure on strains in concrete cylinders. However, the writers do not consider that these tests were conclusive, and believe that more experimental work is needed in this field.

It is believed that much more laboratory work—not haphazard testing, but rather fundamental research—is needed before the mechanism of frost action can be satisfactorily explained. However, the research should not be restricted to the laboratory, for, as demonstrated particularly by recent work of Tremper‡ and Jackson**, valuable clues can be obtained from field inspections. The so-called D-cracks which are often found in concrete structures subjected to freezing and thawing have not been satisfactorily explained. The D-lines which are close to and roughly parallel to edges have been interpreted by some observers as a result of ice segregation.

By A. R. COLLINS§

Mr. Powers' excellent paper has been read with very great interest. He writes with the advantage of having a backing of unpublished data to

*Serge Leliavsky, "Uplift in Dams," *Nature* (London) No. 3770, p. 137 (1942)

†Karl Terzaghi, "Simple Tests to Determine Hydrostatic Uplift," *Eng. News-Record*, v. 116, p. 872 (1936).

‡Bailey Tremper, "The Effect of Alkalies in Portland Cement on the Durability of Concrete," *A.C.I. JOURNAL*, Nov. 1944, p. 89.

**F. H. Jackson, "Disintegration of Bridge Concrete in the West," *Public Roads*, v. 24, No. 4, p. 98 (1945).

§Department of Scientific and Industrial Research, Road Research Laboratory, Harmondsworth, West Drayton, Middlesex, England.

support his hypothesis and detailed discussion is, therefore, rather difficult.

Mr. Powers' hypothesis appears to provide a good explanation of most of the data obtained in laboratory tests and perhaps also in some field conditions, but it is felt that there are some circumstances, particularly in regard to concrete pavements, in which ice segregation provides a better explanation of the observed phenomena. This may mean that damage is caused by different mechanisms according to the conditions of freezing and the type of concrete concerned. It appears that Mr. Powers recognizes this possibility when, on page 267, in doubting the validity to the application of the ice segregation theory to concrete, he expressly confines his remarks to freezing in laboratory conditions.

The evidence that suggested ice segregation as the cause of damage in field conditions was obtained in England in early 1942. There was, at that time, an unusually long, severe and continuous frost with little or no intermediate periods of thawing. Throughout the freezing period pavement concrete of poor quality on a certain site appeared to be undamaged, though it was not subjected to traffic. When the final thaw occurred, however, a spectacular failure took place, the concrete being broken up in horizontal layers to its full depth of 6 in. This failure seems to be more easily explained by the formation of ice lenses than by hydraulic pressure.

In laboratory tests in which freezing was applied to one face of the concrete and a water reservoir maintained at the opposite face (conditions which more closely represent practice than the usual freezing test), the total moisture content of the specimen at the end of one period of freezing and before thawing was found to have increased. This suggests a process of ice crystal growth rather than one in which the water is forced away from the cold face. Similar observations have been made on stabilized soil frozen in the same way. There is also direct evidence of ice crystal growth in concrete in the appearance of sizable ice crystals beneath, and supporting, a scale of concrete forced off during freezing*, the volume of ice being much greater than that of any water that could have been driven from the scale by freezing. This phenomenon appears to be similar to the formation of the so-called "fibre ice" under the particles of soil lifted in the same way and reported by Ruckli†.

As Mr. Powers suggests, further tests are clearly necessary to establish the behavior of water in concrete during freezing, but in making these tests we must be sure that a wide range of both laboratory and field conditions are covered. It might then be found that the mechanism of

*A. R. Collins, "The Destruction of Concrete by Frost," *Jour. Inst. C. E.*, 1944, 23(1), 29-41.

†R. Ruckli, "Die Gefährlichkeit des Strassenuntergrundes," *Strasse und Verkehr*, 1943, 29, (19), 311.

failure may vary according to the properties of the concrete and the freezing conditions.

AUTHOR'S CLOSURE

The written discussions submitted by Mrs. Terzaghi, Messrs. McHenry and Brewer and Mr. Collins, together with many oral discussions with Messrs. Pickett and Steinour of this laboratory have been very helpful in further developing, clarifying and modifying the author's hypothesis. This will be apparent in the following discussion of some of the written discussions of the paper.

From the information given by Mrs. Terzaghi and by Messrs. McHenry and Brewer concerning the fraction of cross sectional area contacted by the mobile water in saturated concrete, it appears that the author's computation of the hydraulic pressure required to produce stress equal to the strength of concrete gave a result that is too high. If the area of contact is 100 percent, the tensile stresses developed under the conditions assumed would be five times as high as those estimated by the author, as Mrs. Terzaghi has pointed out. This would seem to increase the force of the author's argument that disruptive hydraulic pressures are likely to develop through the displacement of unfrozen water.

Mrs. Terzaghi's computation indicated that among grades of concrete originally used, the critical depths of saturation range from 0.2 in. to 7 in. for cooling at a "natural" rate. This too might be taken as added support of the hypothesis but for the fact that the basis of the computations is incorrect. For her computations, Mrs. Terzaghi adopted the same simplifying assumptions used by the author for the purpose of illustrating the principles on which the hypothesis is based. Unfortunately, these assumptions are not permissible for a computation such as Mrs. Terzaghi undertook. The author assumed that all the freezable water would freeze at the same time. This would probably be not very far from the truth for small specimens rapidly cooled to a very low temperature.* Mrs. Terzaghi not only adopted this assumption but also the further assumption that all the freezable water would freeze "at or slightly below 32 F." This latter assumption is definitely not acceptable for such a computation, for when concrete is cooled comparatively slowly, there must be a considerable time-lag between the first and final freezing in a given region, if supercooling does not occur.

An example of melting-data for water in a saturated cement paste is:

*Nevertheless, had the significance of progressive freezing been realized at the time (see below), this assumption would not have been made, even though the author's aim was restricted to illustrating the general principle involved.

Temp. deg. C	Amount of Ice, g/g of cement	Amount of Ice as per cent of Amount at - 15 C
0	0	0
-0.25	.045	21
-0.75	.075	36
-1.00	.093	44
-1.50	.109	52
-2.00	.122	59
-2.50	.131	62
-3.0	.137	65
-4.0	.147	70
-6.0	.168	80
-8.0	.181	86
-15.0	.210	100

From this it must be concluded that the amount of water freezing at any one time and place is much less than the total freezable water as defined in the paper.

Further consideration of this phase of the hypothesis gives rise to the following speculation: Since the water may freeze progressively as the temperature falls, the ice content will have a gradient

$$\frac{di}{dz} = \frac{di}{d\theta} \cdot \frac{d\theta}{dz}$$

where $\frac{di}{dz}$ = the ice-content gradient

$\frac{di}{d\theta}$ = the change in ice content per degree drop in temperature

$\frac{d\theta}{dz}$ = the temperature gradient.

This would indicate that the ice that forms at low temperature would form in spaces already partially or wholly surrounded with ice formed earlier when the temperature was higher. The passages would either be much restricted or wholly blocked by the earlier-formed ice and thus the pressures generated by the formation of the ice at low temperature might be much higher than would be estimated from the normal permeability of the concrete. Also it might be of more nearly static nature than was first supposed.

For the sake of simplicity the author assumed that the saturated region of the concrete was fully saturated and that when this region froze, the displaced water flowed across a sharp line of demarcation into a region containing no freezable water. This was pointed out as an oversimplification (see pages 254 and 255) justifiable only for the purpose of providing a simple illustration of the principle on which the hypothesis is based. The oversimplification results in an underestimate of probable hydraulic pressure when applied to the problem attacked by Mrs. Terzaghi. To illustrate this point, we may imagine a case wherein, at saturation, the amount of water freezable at -15°C is n grams per cu. cm of concrete. We will assume that the specimen is saturated to the depth z , that the freezable water content of the rest of the specimen is $0.9n$, and that the mobile water content at saturation is equal to the freezable water content. When the saturated region is frozen to a depth of 1 cm, about $0.1n$ cu. cm of water will be forced into the region already containing $0.9n$ cu. cm of freezable water per cu. cm of concrete. Therefore, for each cu. cm of saturated concrete that is frozen, 1 cu. cm of the partially saturated region would become saturated. Thus, the depth of the saturated zone, under the conditions assumed would increase at the same rate as the rate of freezing.

This too is an oversimplification acceptable only for the purpose of illustration. Experiment shows that, except for very porous concrete, water does not penetrate dry concrete in such a way as to give a sharp demarcation between the saturated and unsaturated zones. Instead, the process resembles diffusion in that a moisture gradient develops that becomes flatter the farther the water moves into the dry interior. This fact and the probable effect of progressive freezing on permeability as discussed above would have to be taken into account to reach even an approximate solution of the problem attempted by Mrs. Terzaghi.

Mrs. Terzaghi feels that lean concrete is not likely to become saturated to a depth of 7 in. and because of this opinion she feels forced to the conclusion that frost damage to lean concrete is generally due to some process other than that postulated by the author. Such a statement indicates that the discussion of the possible role of dynamic pressure in the destruction of laboratory specimens tended to obscure the importance of static pressures in general. The hypothesis is based on the premise that the destruction of concrete is caused by hydraulic pressure generated by the expansion accompanying the freezing of water (see p. 246). This pressure may be either static or dynamic. As pointed out on page 257, failure because of static pressure will occur when escape from a saturated region is impossible, even though the depth of saturation is less than the critical depth.

To illustrate further: It might be surmised from a part of the hypothesis that a 6-in. retaining wall made of concrete having a critical depth of saturation of 7 in. would never be damaged by freezing and thawing. Such a conclusion should not be reached on the basis of the whole hypothesis, however. Failure might occur through unsound aggregate particles or it might occur as follows: Suppose the wall to have become saturated from ground water and rain and that it has become frozen by a gradual drop in temperature without appreciable damage to the wall. If the exposed side then thaws to a depth of, say, 1 in. with perhaps rain or melting snow to keep the surface saturated, a subsequent drop in temperature could cause damage by trapping unfrozen water between the ice formed near the exterior and the ice still in the interior. Under such a condition the failure would be caused by a static pressure.* To be considered also is the probable effect of progressive freezing on permeability, discussed above. Probably the critical depth of saturation in lean concrete is much less than was indicated by the result of Mrs. Terzaghi's computation.

Regarding the probability of ice-segregation in concrete: As Mr. Collins observed, most of the discussion in the paper pertained to the probability of lens-formation under laboratory-test conditions. The author agrees that there must be some condition of cooling that could produce ice-segregation if the condition is maintained long enough, and if the concrete next to the lens is kept virtually saturated while the lens grows. The question is whether such a condition is ever found in the field, or at least whether it is found frequently enough to be considered the usual mode of concrete destruction by frost action. The author still sees little possibility that segregation can occur, even in the field, because of

- (1) the relatively low freezable water content,
- (2) the smallness of the portion of the total freezable water that is freezable near the normal freezing point,
- (3) the "self-desiccation" caused by cement hydration,
- (4) the relatively low permeability, and
- (5) the rigidity of the concrete.

I must disagree with Mrs. Terzaghi's statement that there is nothing in Taber's observations to indicate that low permeability is an obstacle to ice-lens formation. In his paper "Freezing and Thawing of Soils as Factors in the Destruction of Road Pavements" *Public Roads* V. 11, 113 (1930), Taber states: "In laboratory tests, soils that are very impermeable because of high colloid content behave essentially as closed systems, the amount of heaving being the same whether the containers

*This explanation was given by Kreüger (ibid.) for certain types of masonry failures in buildings.

are sealed at the bottom or whether they are perforated and stand in water. The surface uplift in both cases is equal to the change in volume of the water frozen. . . . The only soils thus far tested that behave on freezing like closed systems, because of impermeability, are certain muck and gumbo soils, and soils containing bentonite." In the *Jl. of Geology*, V. 38, page 306, Taber says, "As the resistance to movement of ground water increases, an open system tends to grade into a closed system." In the laboratory Taber succeeded in producing ice segregation in mixtures containing bentonite, but in order to do this he found it necessary to "mix the bentonite thoroughly with water before placing it in cartons." The point is that when a system contains a large amount of readily freezable water, as did Taber's laboratory preparations containing bentonite, and probably the saturated clay shown in McHenry and Brewer's Fig. D, perhaps 30 to 40 per cent of the over-all volume, lenses could form under ordinary cooling conditions by extracting water from the material immediately adjacent to the points of lens formation. Also, in such specimens, most of the freezable water is freezable near the normal freezing point. Permeability becomes a deciding factor when the material close to the zone of freezing does not contain enough readily freezable water to produce a visible lens.

The part that permeability plays in the phenomenon of ice segregation can readily be illustrated by means of Fig. 1 of the paper. For the present purpose imagine the concrete represented in Fig. 1 to be saturated throughout and in communication on the right-hand side with a supply of water. Heat is being extracted through the layer of ice at the left. Under certain conditions of cooling the water in the concrete will not freeze; instead, the thickness of the ice coating will increase by extracting water from the concrete.

The conditions under which this phenomenon will occur are those in which heat is removed at a rate just sufficient to freeze the water as it is extracted from the concrete. If heat is removed at a greater rate, the temperature will fall and the zone of freezing will move into the concrete. Since the rate of flow of water from the concrete depends on permeability the permissible rate of heat removal for ice lens formation obviously depends on the permeability of the concrete.

It is true that segregation occurs only in granular materials of relatively high specific surface, as Mr. Terzaghi pointed out. But this fact is not incompatible with the conclusion reached above.

This discussion is intended to show the conditions that must be maintained while a given ice-lens grows. It does not deal with the conditions that must be met for an ice-lens to start within a rigid material like concrete. As Messrs. McHenry and Brewer point out, the tensile

strength of the concrete must be overcome before a lens can start, unless it starts from water in a macroscopic cavity and even then it cannot grow beyond the cavity without rupturing the concrete.

Mrs. Terzaghi and Messrs. McHenry and Brewer express similar views concerning spaces between the aggregate and the paste. These spaces can undoubtedly be sources of disruptive hydraulic pressure, or perhaps of the growth of ice lenses, but only after the concrete has been subjected to prolonged external hydraulic pressure of considerable intensity. The condition of specimens after permeability tests, as mentioned by the discussers, shows that such spaces may become filled, at least partly. Also, this is indicated by pressure cells embedded near the upstream face and near the base of a high dam. But experience shows that in concrete of good quality, under conditions where external hydrostatic pressure is low or absent, the fissures under the aggregate become empty and the original air-filled cavities remain empty. Moreover, the capillary system of the paste itself becomes partly empty. When the primary cause of water-movement into such concrete is capillary absorption, water would move into such spaces last, if at all. Hence, fissures and other cavities in laboratory specimens, pavement slabs and other members not subjected to prolonged high pressure, should, according to the hypothesis, be beneficial to frost resistance. The known beneficial effect of entrained air is strong support to this conclusion. Also, we have data indicating that the under-aggregate fissures increase the frost resistance of concrete specimens soaked in the usual way before freezing. When powdered minerals are added to lean concrete or mortar, both the air-voids and the fissures are reduced. Such effects are accompanied by *decreased* frost resistance even though strength is usually increased.

Messrs. McHenry and Brewer note that no satisfactory explanation of D-cracking other than ice segregation has been offered. Such cracks, running parallel to each other and to the edge of a slab, can be explained by the hydraulic-pressure hypothesis.

In wet weather, water accumulates in transverse cracks and joints and in the shoulder next to the edge of the pavement. Usually water is retained in these regions long after the surface of the slab becomes dry. Consequently, the margins of the slab tend to become and remain saturated. When freezing of the saturated margins occurs, pressure is developed in them tending to expand and rupture these saturated margins. However, expansion in a direction parallel to the edge is restrained by the unsaturated portion of the slab and therefore cracks due to freezing never run perpendicular to an edge as shrinkage cracks do. The D-crack first formed readily carries water and thus aids in increasing the width of the saturated margin and thereby promotes the formation of additional parallel cracks when freezing again occurs.

A proper rate of cooling could produce surface scaling by means of ice-segregation, but it appears more probable that scaling occurs when saturated surface layers are literally pushed up by the hydraulic pressure.

The writer believes that leaching of lime and alkalies from the margins of a concrete slab is a factor hastening the process and possibly is essential to it. Leaching coarsens the texture of the paste and thereby increases its capacity for freezable water. Such an increase in freezable water increases the amount of water that must be forced into the unleached and only partially saturated region in a given length of time and would thus result in increased hydraulic pressure.

Regarding Fig. 2 on page 258: This laboratory has data, like those mentioned by Messrs. McHenry and Brewer, that apparently contradict the results given in Fig. 2. Yet we can find no basis for discarding the results shown in Fig. 2; they, as well as different results, must eventually be explained. Possibly the peculiar combination of size of specimen, amount of water around the specimens, rate of freezing and manner of thawing, and the treatment of the specimens before the cycles began would have to be duplicated exactly to get the same results. Such apparent discrepancies between the results from different laboratories, and indeed from one laboratory, show the need for establishing a test procedure that is based on a better understanding of the mechanism of frost action than we now have.

In the original paper the writer neglected to mention recent papers by H. L. Kennedy.* Some of the basic ideas on the mechanism of frost resistance given in my paper are similar to those published by Mr. Kennedy.

*H. L. Kennedy, ACI JOURNAL, June 1944; V. 40, p. 515.
H. L. Kennedy, Proc. A.S.T.M. V. 44, 821 (1944).



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